AIAA SciTech Forum
9 - 13 January 2017, Grapevine, Texas
55th AIAA Aerospace Sciences Meeting

10.2514/6.2017-0462

Requirements Analysis for Design Optimization of Aerobatic Aircraft

Darshan Sarojini*, Kyle Collins†, Dimitri N Mavris‡
Georgia Institute of Technology, Atlanta, Georgia, 30332, USA

Aerobatic aircraft design and simulation is challenging as these aircraft need to fly at any angle of attack and sideslip angle (full-envelope aerodynamics). They fly at velocities close to stall speed, all the way upto the never exceed velocity. These aircraft are also routinely stressed to 6-12 g's in both upright and inverted flight. Presently, most aerobatic aircraft are designed using heuristic knowledge. There is a need for a systematic approach to design aerobatic aircraft in a multi-disciplinary design framework. Towards this goal, this paper presents an extensive study of requirements, metrics and design variables to define a good aerobatic aircraft. First a historical perspective is given to know the current state-of-the-art. Information obtained from regulations, aircraft performance, subject matter experts and analysis of existing aircraft is used to obtain metrics to evaluate. The possible design configurations is given as a morphological matrix. Finally, possible analysis approaches to evaluate the metrics are discussed.

Nomenclature

P_{ref}	Power of engine
W_{TO}	Take-off gross weight
β	Fuel fraction at start of a maneuver
α	Thrust lapse rate
π_η^+	Propeller efficiency
q	Dynamic pressure
K_1	Induced drag term
e	Ostwald efficiency factor
AR	Aspect ratio
n	Load factor
C_{D_0}	Zero lift drag coefficient
V_∞	Free-stream velocity
e	Ostwald efficiency factor
$\frac{dh}{dt}$	Rate of climb
g_0	Acceleration due to gravity
V_S	Stall speed
$C_{L_{max}}$	Maximum lift coefficient
b	Wing span
W_E	Empty weight
V_{NE}	Never exceed velocity
V_{max}	Maximum level speed
$\dot{\phi}$	Roll rate
P_A	Power available
P_R	Power required
T	Aircraft instantaneous thrust
D	Aircraft instantaneous drag
S	Wing area

I. Introduction

Aerobatic aircraft like the Edge 540 (Fig. 1) or the Pitts (Fig. 2) form a category of aircraft with unique requirements such as high thrust-to-weight, high roll rate, ability to sustain high g's, ability to fly in all attitudes (full-envelope aerodynamics) and good handling qualities for high maneuverability. Aerobatic aircraft are flown and stressed to the limits of both the plane and the pilot. Todays unlimited aerobatic aircraft routinely fly with 6-12 g's in both the positive (upright) and negative (inverted) attitudes. In addition, the planes fly with zero lift on the wing at zero airspeed- if you can call that flying- all the way up to V_{NE}, the never exceed velocity and pretty much anything in between. The construction of these aircraft

*Graduate student, School of Aerospace Engineering, Aerospace Systems Design Laboratory
†Research Engineer, School of Aerospace Engineering, Aerospace Systems Design Laboratory
‡Boeing Regents Professor of Advanced Aerospace Systems Analysis, School of Aerospace Engineering, Aerospace Systems Design Laboratory

takes the form of tried and true tube and steel fuselage with wooden wing spars all the way up to state of the art carbon fiber construction throughout. This makes aerobatic aircraft design and flight simulation an excellent area of research that can be applied to many problems in general aviation. In a similar way that R&D groups in Toyota and Honda focus on racing, the study of aerobatic aircraft design and flight simulation will illuminate ways to optimize highly maneuverable aircraft, lighten aircraft structures safely, recover from loss of control, enhance emergency escape systems, and make aircraft easier to fly in all attitudes.

Figure 1: Edge 540

Figure 2: Pitts

Aerobatic aircraft are flown predominantly in two different scenarios: competition aerobatics and air races. Competition aerobatics takes place in an aerobatic box as shown in Fig. 3. Fig. 4 shows the aresti symbol notation used to describe figures in the sportsman, intermediate, advanced, and unlimited categories of the international aerobatic club. As seen, the sequences get more complicated from sportsman to unlimited. Inverted snap rolls and tailsides are unique to the unlimited category.

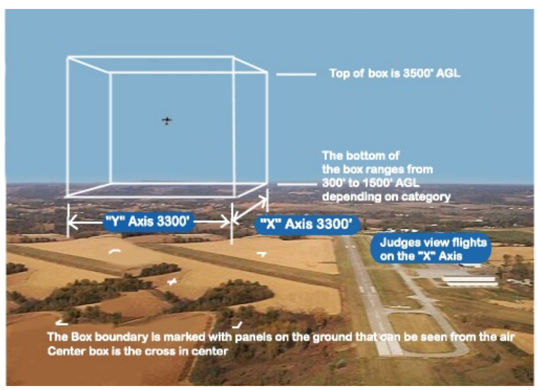

Figure 3: Aerobatic Box

The requirements for the Red Bull Air Race are different from those of the world aerobatic competition. In the Red Bull Air Race, the goal is go around a track in the least time possible. Most of the flight is positive (upright) and maneuvers like snap roll are not required to be performed. On the other hand, unlimited aerobatic competition aircraft must execute multiple maneuvers, many of which are in inverted flight. Today, pilots use similar aircraft for both competitions.

Most aerobatic aircraft today are designed using heuristic knowledge. To create the next best aerobatic aircraft, designers embark on a process that is aimed at making the desirable qualities of the current best aircraft better, while reducing or removing any negative traits. The designers are thus trying to optimize the design. The objective function may contain one value; for instance, maximize height achievable from a 3G vertical pull-up from 120 miles per hour. Or it may contain multiple, possibly conflicting objectives like reduce weight, balance stick forces, increase low speed roll rate, reduce energy loss, increase safety, reduce cost and maximize the speed at which flutter occurs.

A thorough evaluation of the full envelope aerodynamics of an aerobatic aircraft in flight has been of great interest recently with the introduction of UAVs, as signified by the number of papers written on this

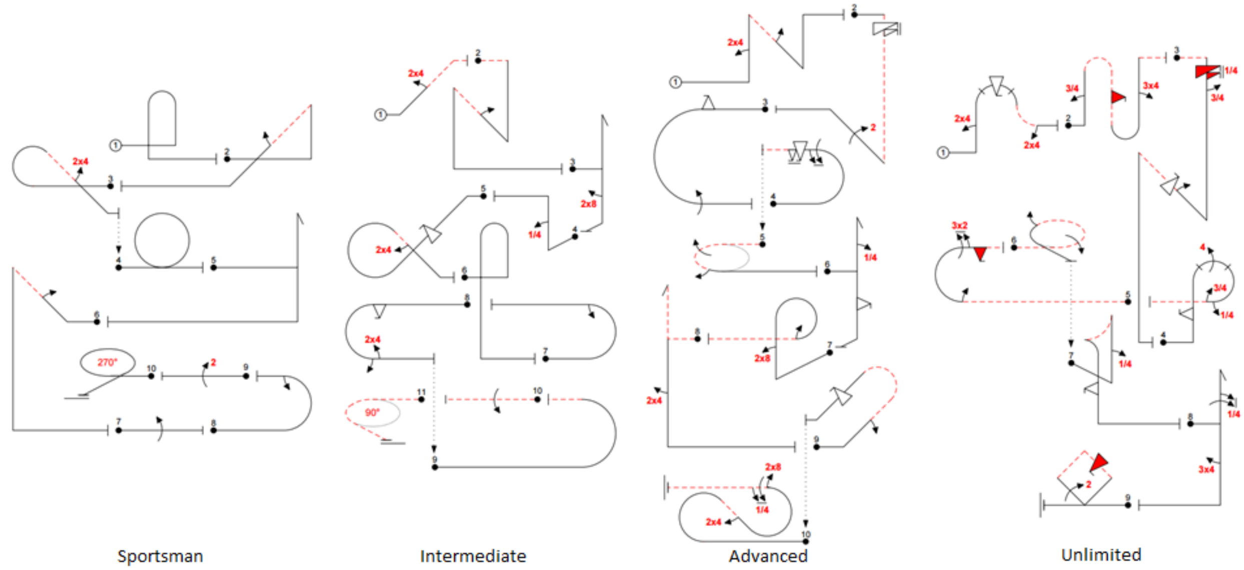

Figure 4: Categories in competition aerobatics. Dashed lines represent inverted flight. Arrows represent rolling elements. Isosceles triangles represent snap rolls and right angle triangles represent spins. Filled triangles represent negative snap rolls and spins.

topic. Many methods have been employed by researchers to achieve this; by creating a a highly-instrumented 35%-scale model of the fullscale Extra 260 aerobatic aircraft,[1] by creating a model based on first-principles aerodynamic modeling supported by lookup tables,[2] and by wind tunnel testing.[3]

Existing papers relating to the evaluation and optimization of aerobatic aircraft performance do not define an objective function for the goodness of the aircraft as a whole. In the past, efforts have been made to achieve an optimal design for an aerobatic aircraft wing structure given the weight, strength and aeroelastic requirements.[4] This was done by employing analytical and finite element methods for structural analysis and defining an objective function that maximizes wing flutter speed as a function of lamina fiber orientation angles within the composite wing. While this objective function is used to solve an optimization problem, it does not consider the performance of the aircraft; the only factors optimized are the structural rigidity and the weight of the wing.

This project aims to develop a methodology to design aerobatic aircraft. The overall methodology being followed is shown in Fig. 5. The focus of this paper will be on the metrics to define goodness of aerobatic aircraft. The reason for this is that before trying to optimize a design for aerobatic aircraft, the metrics that will make up the objective function must be clearly defined and substantiated. Metrics are obtained from regulations, performance analysis, Subject Matter Expert (SME) opinions and a survey of existing aircraft.

Section 2 gives a brief history of aerobatic aircraft. Section 3 attempts to start defining the metrics of goodness. Section 4 includes a survey of existing aircraft. Section 5 discusses aspects of optimization, design variables of interest and possible analysis methods to evaluate them.

II. History of Aerobatic Aircraft

This paper is not meant to be a history of aerobatics or the aircraft used in such endeavors. However, a brief discussion of the more recent history or evolution of aerobatic aircraft design is certainly pertinent to the discussion of what makes and aerobatic aircraft good. Other disclaimers are also necessary. Foremost, some of the information presented in this section are taken from what has been learned from Wikipedia pages and other internet content that is difficult to cite. Other information was gained through conversations with many aerobatic pilots and people involved with the sport for a long time. Secondly, a lot of detail is left out. Future work will scrutinize more throughly the differences in the various aerobatic aircraft designs flying competitively today. This implies analyzing the geometry, airfoil selection, planform shape, empennage location, control surface size, control system configuration, material and construction methods, and other

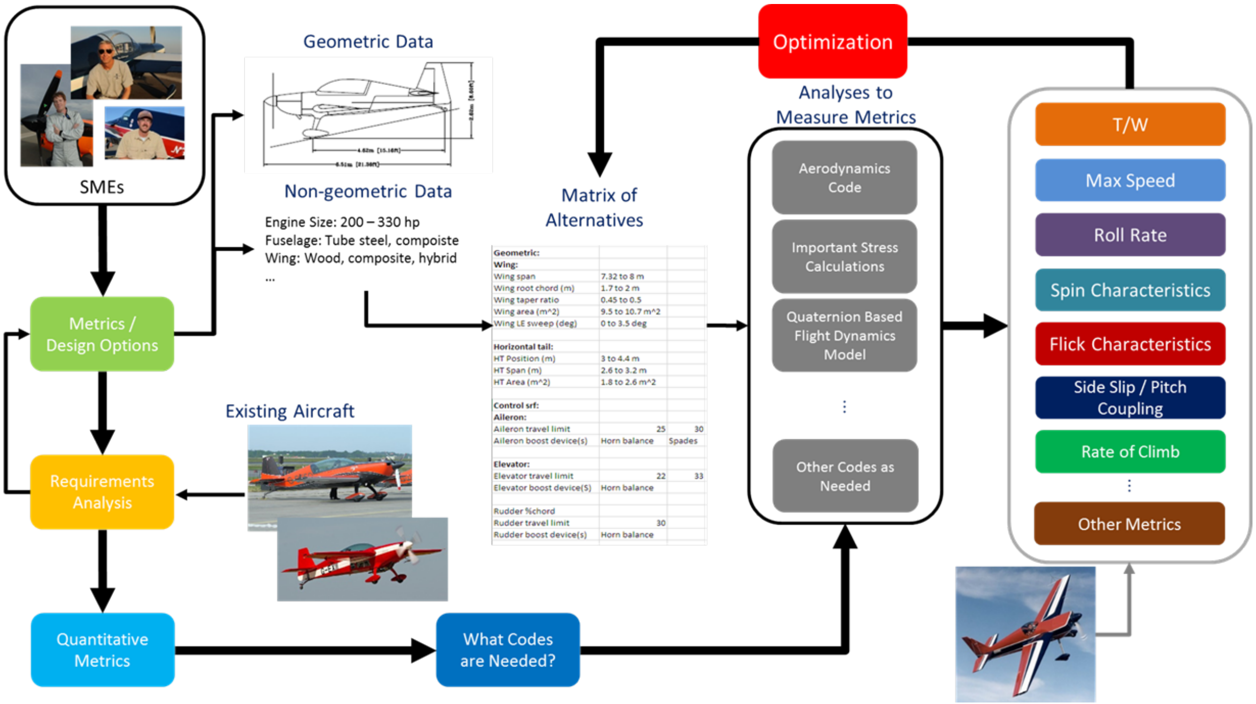

Figure 5: Aerobatic aircraft design methodology

aspects that differentiate the alternative design choices seen in the field. Going into this detail now however, is out of the scope of this section and this paper.

An aircraft that has left a very large mark on the field of aerobatic competition over the last 70 years has been the biplane designed by Curtis Pitts. The aircraft shared his name and comes in many variants, both 1 seat and 2 seat versions. The Pitts S1-C had semi-symmetrical or cambered airfoils. The S1-S had symmetrical airfoils. Both aircraft designs can be found in factory built or factory kit built and utilize the 4-cylinder Lycoming engines with horsepower ratings ranging from 160 to 230 HP. The factory built, certified S1-T had a 4-cylinder, 200 HP engine with a constant speed propeller. The S2-A was a 2-seat version with a 4-cylinder, 200 HP engine and constant speed propeller. The S2-B and the most current version, the S2-C sport 6-cylinder engines with upwards of 260 HP. Curtis Pitts patented the biplane wing arrangement[5] in order to achieve a balanced design in both positive (upright) and negative (inverted) flight. The aircraft are simple in construction using tubular welded steel fuselage and wooden spar wings. Both fuselage and wings are fabric covered. Despite the age of the design, these aircraft are still competitive in all categories of competition. However, most pilots entering a Pitts into unlimited competition rely on the 6-cylinder S2 models. Readers who want to learn more about the Pitts design and models not mentioned like the S1-11B and S2-S, are encouraged to read articles by Budd Davisson found here [www.airbum.com/pitts.html].

Though the Pitts is still competitive, the rise of the monoplane as the premier aerobatic mount has most pilots moving to this design if they want to rise up in the ranks as an advanced or unlimited competitor. Thus, the following discussion is focused on the monoplane design and some of the models that have heavily influenced the sport. Many monoplane designs can trace their heritage back to a model called the Stephens Akro. This homebuilt aircraft was designed and built in the 1960s by Clayton Stephens. A very famous aerobatic pilot by the name of Leo Loudenslager built a version with many aspects modified. This modified version was called the Laser 200. It used a 4-cylinder, 200 HP engine. Later versions of the design utilized higher compression cylinders to pump up the output to 230 HP. Due to this increased horsepower, these models are given the name Laser 230. The construction of the Stephens Akro and Laser 200/230 models was welded tubular steel fuselage and empennage with a primarily wooden wing structure.

A German aerobatic pilot named Walter Extra built a Laser 230 for himself. Friends of his wanted him to build them a copy as well. He did and so began his career as an aircraft manufacturer. He called his modified version the Extra 230 and began production around 1986.[6] Extra went on to produce a 6-cylinder version in the Extra 300. The construction of the Extra utilizes a welded tubular steel fuselage with a composite spar wing. Unlike the Laser and Pitts which have tubular steel welded empennage, the Extra uses composite construction allowing the horizontal and vertical stabilizers to have an airfoil shape as opposed to a flat plate profile. The marriage of tubular steel fuselage and composite wing and tail have proven to be a good fit and have given the Extra the reputation as a highly reliable airframe.

The Laser 230 also spawned another winning design led by Zivko Aeronautics.[7] Zivko designed a wing for the Laser 230 utilizing their experience in composite construction. The result was a very rigid wing with good aerodynamic qualities and an ultimate load of 20+ Gs. The wing airframe combination was called the Edge 230. Zivko expanded the project to develop a larger, 6-cylinder version requiring a new airframe design as well. The resulting design was called the Edge 540. This single seat aircraft, first flown in 1993, is still very competitive today in both aerobatic competition and the Red Bull Air Race.

In the early 1990's Richard Giles and Martin Hollmann designed the all graphite single seat Giles G-200. A 2-seat version coined the G-202 was later designed. Both designs used the 4-cylinder Lycoming 0-360 engine with 200 HP. The all graphite construction allowed for a very rigid airframe with near full span ailerons. Subsequently, the aircraft had a tremendous roll-rate, on the order of 400-500 deg/sec. The aircraft boasts unlimited performance on a 4-cylinder fuel bill. The all carbon fiber construction produced a lightweight structure helping to increase the power to weight ratio, a very important metric for aerobatic flight.[8]

The MX design was an evolution from the Giles, designed by Chris Meyer.[9] The wing was changed as well as the fuselage length to account for the larger 6-cylinder Lycoming strapped to the front. Rob Holland, a 6 time US Unlimited Power Champion flies a customized single-seat model, the MXS-RH. The company MX Aircraft at present time is no longer in business and the future of the MX line of aircraft is uncertain.

In Europe, Philipp Steinbach designed the composite Sbach 300[10] which evolved into the Sbach 342;[11] and later these SBach designs became the Xtreme air X-41 and X-42, 1 and 2 seat versions of the 6-cylinder 300 to 300 plus horsepower all carbon composite aerobatic machines. Prior to this, Philipp gained experience with aerobatic aircraft design and manufacture working for Walter Extra at Extra aircraft. Now, Philipp is working on a new soon-to-be certified aerobat called the Gamebird 1 from Gamebird Composites,[12] a company founded by Steinbach and Steuart Walton. The designs of Phillip share the same curvilinear shapes in all aspects that make it look very flowing from propeller to rudder.

Other aircraft designs that need to be mentioned are designs by Sukhoi, Yakovlev, Aviatika, and CAP. The designs notable here are the Sukhoi Su-26, Su-29, Su-31, the Yakolev Yak-55, all of which utilize the 9-cylinder Vedeneyev M-14 engines, and the CAP 231 and 232 which both utilize the 6-cylinder Lycoming engines. The Sukhoi aircraft are built primarily from composite with carbon wing spars. The Yak-55 has a more traditional construction with semi-monocoque metal construction with a metal cantilevered spar configuration. The Aviatika-MAI-900 Acrobat is similar to the Sukhoi design but with unique patented differences.[13]

Thus, the field of top, state of the art unlimited aerobatic aircraft can be summarized by looking at the machines featured in the World Unlimited Aerobatic Championships in 2015. The machines listed in the general results include: Extra 330SC, Sukhoi 26M, XA-41, CAP 332, SU31M, Extra 300SR, MXS, Edge 540, Sukhoi 31, Sbach 300, Laser, and CAP 231EX. A notable aspect of this is that 27 of the 58 competitors flew the Extra 330SC. That is 47%. And the top two places also utilized this machine. But this alone is not enough evidence to crown the Extra 330SC as the absolute best machine. However, it does make the authors take notice as we work to understand not only what defines a great aerobatic machine, but also what characteristics, mechanics, shapes, parameter values, engine and propeller combination can lead to optimum designs. But as all current aerobatic pilots know, the 330SC is expensive, costing more than $400,000 dollars to purchase new.

Can optimization be used to design an aerobatic aircraft with similar characteristics but at a lower cost to purchase and operate? Students at Sherbrooke in Canada designed and built a single seat, all composite aerobatic aircraft called the Epervier.[14] The aircraft was powered by a 75 HP rotax engine, thus making it very economical to operate. Also, Paulo Iscold, the Brazilian professor who works as a race tech / track optimization guru for Team Chambliss in the Red Bull Air Race designed a single seat, 4-cylinder aerobatic aircraft called the CEA-309 Mehari Aerobatic Aircraft[15,16] as well as the Anequim,[17] an aircraft that broke a world speed record.

This brief look at the history of aerobatic aircraft and the machines that have evolved to the state-of-the-art unlimited machines of today only scratches the surface of the technical analysis that could be performed by analyzing the designs in detail. The authors recognize that this type of analysis, combined with eliciting comments from pilots who have flown a number of the designs, would provide a good basis for understanding what works, what does not, and what aspects of the flying characteristics certain design choices cause. This analysis however, is out of the scope of this paper, which is mainly meant to focus on the metrics used to judge goodness. Diving into an in-depth analysis of current and past aerobatic aircraft designs is the subject of future work. That being said, some discussion of design features are mentioned in this paper where appropriate.

III. Metrics to Evaluate Goodness

Understanding the mission requirements is a crucial part of designing new aircraft. For conventional aircraft design, the objectives may include a target max range, cruise speed, operational ceiling, max payload and weight. Broadly, the objective of an aerobatic aircraft is to be able to perform unusual maneuvers which require extreme maneuverability and power. While many aircraft are capable of being aerobatic, it is less clear how quantifiable aircraft specifications such as power to weight ratio, climb rate, etc. relate to its ability to perform aerobatics. A more methodical approach to designing aerobatic aircraft would necessitate understanding how these performance metrics impact aerobatic ability, and what will constrain the design. Using a combination of literature review, examination of both the history and state-of-the-art in aerobatic aircraft design, and information received from highly skilled aerobatic pilots, plane designers, and manufacturers, the authors have compiled a list of attributes that should be considered when designing an aerobatic aircraft. The following sub-sections will go through these attributes and discuss both the subjective and quantitative metrics that can make a difference.

A. Safety

While almost all aerobatic pilots want a more capable aircraft in terms of power to weight, low speed roll rate, and energy conservation during maneuvers, few are willing to accept the increased capability if it meant a compromise in safety. Aerobatic aircraft must be designed and built to exacting standards as they are repeatedly stressed to high positive and negative g's and rapid maneuvers. Some requirements for safety can come directly from the federal aviation regulations Part 23, which contains the airworthiness standards for normal, utility, acrobatic, and commuter category airplanes. These standards ensure a level of safety that is typical of a certified aircraft. Other safety related requirements may be derived from experience or novel ideas aimed at increasing the safety of the sport of aerobatics beyond what can be had from following part 23 alone.

1. Stall Speed

14 CFR 23.49 specifies that the stall speed should be no greater than 70 mph. This is applicable to all categories, including aerobatic.

2. Spin Recovery

14 CFR 23.221 specifies how the various category of aircraft must recover from a spin. “A single-engine, normal category airplane must be able to recover from a one-turn spin or a three-second spin, whichever takes longer, in not more than one additional turn after initiation of the first control action for recovery, or demonstrate compliance with the optional spin resistant requirements of this section.”Also, “the applicable airspeed limit and positive limit maneuvering load factor must not be exceeded; no control forces or characteristic encountered during the spin or recovery may adversely affect prompt recovery; and it must be impossible to obtain unrecoverable spins with any use of the flight or engine power controls either at the entry into or during the spin”. This is also a certification requirement for the utility category. The acrobatic category must meet this plus additional requirements. “The airplane must recover from any point in a spin up to and including six turns, or any greater number of turns for which certification is requested, in not more than one and one-half additional turns after initiation of the first control action for recovery. However, beyond three turns, the spin may be discontinued if spiral characteristics appear”. In addition, “there must be no characteristics during the spin (such as excessive rates of rotation or extreme oscillatory motion) that might prevent a successful recovery due to disorientation or incapacitation of the pilot”.

3. Limit Load Factor

The limit load factors of 14 CFR 23.337 are listed as positive 6 g's and negative 3 g's for acrobatic. This limit load factor should be considered the minimum required design limits. Most designs from the 1980s to today are designed to higher limit load factors. As a general rule, you can expect to see ratings of positive 10 g's and negative 10 g's for most modern aerobatic aircraft. Some older models seen at competition conform to the +6/-3 rating. For example, the American Champion Super Decathlon is rated to +6 g and -4 g. The super decathlon is typically viewed as the beginning aerobatic mount for most pilots and is very competitive in the sportsman category and somewhat competitive in the intermediate category. The Pitts are typically rated to +6 / -3 g's also and are considered competitive up through the advanced category. The stall speed and limit load factors are summarized in a notional VN Diagram shown in Fig. 6.

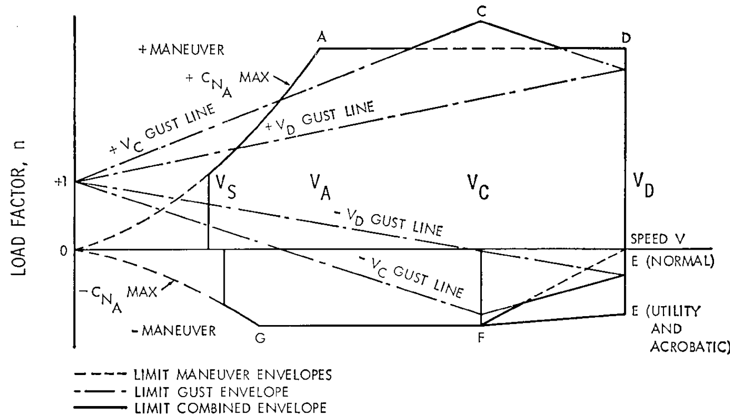

Figure 6: VN diagram with CFR requirements shown.[18] Positive limit maneuvering load factor of +6 (CFR 23.337), negative limit maneuvering load factor of -3 (CFR 23.337), V_S of 61 knots (CFR 23.49)

4. Parachute Backup

The regulation of 14 CFR 91.307 provides that a parachute is necessary when pitch exceeds 30 degrees or bank exceeds 60 degrees if there is a passenger. For solo flight, one does not have to wear a parachute. The regulations also do not have a provision requiring a whole airframe parachute. These are not common on aerobatic planes, but there are examples. Rans Aerobatic Pilot Dino Moline in Argentina was saved by his BRS system in 2010 after losing his left wing in flight during a negative-G push from inverted flight as shown in Fig. 7. The rules of the international aerobatic club (www.iac.org) state that a whole airframe parachute can be used in lieu of a personal parachute. But there is a trade-off. Whole airframe parachutes weigh more than a personal parachute due to the fact that they must be certified for a weight on the order of 1,500 pounds versus a pilots weight on the order of 200 pounds. This added weight reduces the useful load of the design. However, evident from the video of the Rans aerobatic pilot mentioned above, if something goes horribly wrong low to the ground and potentially causing the aircraft to roll or spiral uncontrollably, there is an added level of safety given to the whole airframe parachute and the procedures for its activation which is to simply pull a lever. When this is compared to the procedures for exiting the aircraft and deploying a personal parachute, which includes releasing the restraining harness, opening or ejecting the canopy, climbing out, and deploying the parachute, the benefits are obvious.

An innovation from Russia has attempted to combine the personal parachute with an extremely simplified and rapid procedure in the form of a light aircraft ejection seat shown in Fig. 8. The creators of this innovation are the Research, Development & Production Enterprise "Zvezda". The object of the invention is to create a very light and effective system for the emergency abandonment of an aircraft by a member of the crew, which can be used with aircraft having a flight speed up to 500-600 km/hour. In order to achieve the indicated object, a method is proposed for the emergency abandonment from an aircraft which comprises catapulting a member of the crew and a rescue parachute. At first a pack with the parachute is catapulted and then a member of the crew. Catapulting the member of the crew is carried out behind a suspension-linkage system by means of an ejection mechanism, wherein the force of the latter is directed

Figure 7: BRS:Whole Airplane Parachute[19]

through the center of gravity of the member of the crew.[20]

Figure 8: Zvezda Light Airplane Ejection Seat Test[20]

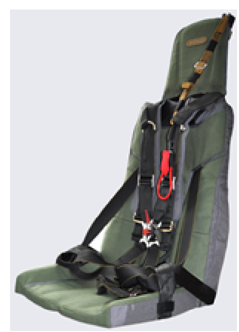

Figure 9: Zvezda Ejection system KS-2012[20]

5. *Control Failures*

A fear of many aerobatic pilots is that at some point during the flight, the controls will not work as intended. This could occur for a number of reasons. Probably the control failure hazard that carries the most risk is something getting caught in the control system and causing a control lock. Because aerobatic planes and their occupants experience all attitudes of flight, it is not unusual for things like coins and keys to fall out of their pockets and make their way into the fuselage. It is rare for these items to cause a control lock, but the risk is there. In her book Fire and Air: A Life on the Edge[21] , Patty Wagstaff recounts a story of an elevator control lock while flying a super decathlon. The culprit was a set of keys that fell from a previous passengers pockets. Obviously, a first line of defense is to ask all passengers to remove everything from their pockets. However, thought of this type of hazard could be given to the cockpit in terms of a design of the interfaces where the controls go from the cockpit to their respective effectors elsewhere. A good design would keep foreign contaminants in the cockpit and not let them into any other area.

B. Performance

The category of performance is somewhat broad and includes several metrics. With regards to performance, the roll rate, weight, and vehicle drag were mentioned as important attributes by SMEs. A SME mentioned that a climb rate of at least 4000 fpm would be beneficial. The overall performance envelope or Velocity-load factor diagram will also include the positive and negative load factor limits as well as the maximum dive speed allowed or V_{NE}. Hence, these parameters are also of importance to the pilot. Some of these metrics are discussed here, while others will be discussed in Section IV.

1. *Spins and rolls*

The roll rates must be high at both high and low speeds. However, since large roll rates in high speed flight may begin to become a negative trait due to the skill required to stop with precision, the designer may choose instead to constrain it to some value within a range, say 400-450 deg/sec. Roll rate in low speed flight, on the other hand, is certainly a criteria to maximize. To perform maneuvers like snap roll, there is a desire to have a higher stall speed.

As shown in Section 3A, in terms of safety, following the requirements of 14 CFR 23.221 should provide the pilot with enough control to safely exit a spin once entered. However, in terms of precision aerobatic competition flying, this may not be enough. In aerobatic competition, spins must be done both positive and negative (inverted), with one to two turns and quarter turns in between. For example, a 1-1/2 turn spin or a 1-1/4 turn spin. This requires the pilot to not only be able to safely exit the spin, but exit it on a precise heading. So this element of precision stopping is another requirement of a good aerobatic aircraft. As noted by a SME, some aircraft are harder to recover from spins, especially inverted spins. This might be, in part, as a result of the rudder area under or above the elevator being small, so the bulk of the airflow across the rudder is blocked during spin.

A SME indicated two metrics which can be used: 1) Roll inertia which is indicative of an aircraft's resistance to roll. This metric allows us to measure the maximum roll rate as well as how quickly the pilot can stop the roll. Hence, this metric would be more appropriate to measure than maximum roll rate, and 2) A sharper tip stall would allow for easier entry into a snap roll or a spin. Monoplanes with symmetrical section tend to have quite blunt-nosed leading edges. Varying the airfoil to have a sharper edge profile outboard would give a good balance between ease of handling and performance.

2. *Max speed and acceleration*

Increasing the maximum level flight speed may be good to a point, but thought must be given to the fact that for aerobatic competition, maneuvers are performed within a box that is $1km^3$. Thus, the faster the aircraft travels, the less time the pilot has to perform figures before he or she has flown out of bounds. One SME pointed out that it is possible that the best aerobatic aircraft might be one in which the velocity on all flight path angles remained constant, similar to what is seen in the world of indoor remote control model aerobatics. In reality with full scale aircraft this would be difficult to accomplish. Because, some figures involve climbs or half loops with level flight after, the aircraft will be traveling at very slow speeds. In these instances, having good acceleration will allow to recover lost velocity in a short distance.

3. *Specific excess power*

Aerobatic aircraft lose energy during figures, high load factor maneuvers, and snap rolls. Energy conservation during figures is closely tied with overall performance of the aircraft. In aircraft performance, specific excess power is defined as

$$P_s = \frac{V_\infty}{W}(T - D) = \frac{P_A - P_R}{W} \tag{1}$$

An aircraft in flight has both kinetic energy and potential energy. These energies can be easily converted to each other by initiating a dive, or by pulling the aircrafts nose up. A flight procedure where one type of energy is converted to the other is called a zoom flight. The energy of the airplane remains constant during a zoom flight. If we define specific energy (also called energy height) as energy per Newton of weight,

$$E_h = \frac{E}{W} = H + \frac{1}{2g}V^2 \tag{2}$$

then the time derivative of energy height gives the specific excess power

$$\frac{dE_h}{dt} = P_s \tag{3}$$

Specific excess power at 1g & std conditions at a typical sequence speed would provide an indication of the vertical performance available from level flight.

C. Handling

All aerobatic aircraft are ultimately flown by pilots. Hence, the handling qualities of the aircraft is a very important category. Like performance, the category of handling qualities is broad as well. In general, the aircraft should be easy to fly.

Many of the SMEs surveyed identified handling qualities as heavily dependent on the pilot. Thus having a control system that can be customized to the individual preferences of the pilot would be a good design feature. While some pilots would prefer a linear control system, others would rather have a greater start-up force that would allow for the control surfaces, particularly the ailerons, to center more quickly. Additionally, those surveyed rated control responsiveness and the necessary applied stick force as important to the control feel of the aircraft.

Another aspect brought up by SMEs is a controllable center of gravity. As a rule of thumb. for precision competition flying the best location is probably 28-29% MAC; whereas for freestyle exhibitions, it would be pushed back to 30%.

In the literature on aircraft handling qualities, the most popular scale used is the Cooper-Harper Ratings.[22] Research into aircraft handling qualities is aimed in part at determining which design variables of the aircraft influence pilot's opinion. Since this can very quickly become a massive combinatorial problem, attempts are made to study one particular aspect while maintaining all others at a fixed value[23] . One such study is shown in Fig. 10.

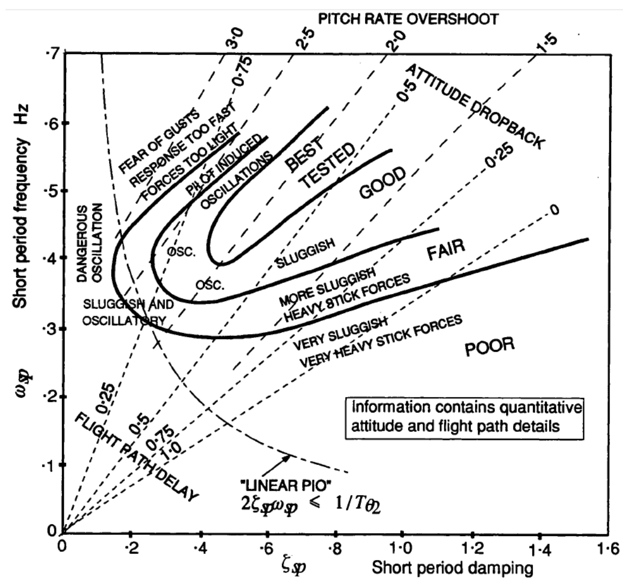

Figure 10: Handling quality information[24]

When operating in the extreme conditions that these aircraft do, control systems must be both reliable and effective, allowing for small and precise movements as well as larger-scale adjustments with maximized pilot comfort and minimal opportunity for failure.

Trim tabs and balance tabs[25] are additional surfaces that can be used primarily to decrease the necessary force input by the pilot. Spades[26] create a force as the control surface is rotated that in turn generates a moment that assists in moving the control surface. The means of connecting the pilots controls to the control surfaces themselves was partially documented in a book by Ian Moir and Allan Seabridge titled *Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration*.[27] They identify Power control units

(PCUs) and spring feel units in the pitch, yaw, and roll controls as necessary to ensure pilot comfort. With regards to the cable and pulley system, they provide detailed diagrams for reference and identify how the use of different-sized pulleys and lever arrangements throughout the system facilitates gearing changes and how tensiometers throughout the system are necessary to ensure there is minimum loss of work.

Ground handling is also important. Most aerobatic aircraft fly with conventional landing gear. Rancourt[14] used a tricycle gear. For tailwheel configurations (conventional), there are steerable vs. free castering type. The Haigh tailwheel assembly is a lockable type, which can improve ground handling, but adds some complexity with a cockpit lock/unlock mechanism requiring a cable to be run from the tailwheel assembly to the cockpit.

D. Cost

A common opinion among SMEs was that most existing aerobatic aircraft can achieve the levels of performances required by unlimited category. The industry is looking for an aircraft with the same levels of performance, but at a lower cost. The cost is not just acquisition cost, but also operating and maintenance costs. The desire should be to make an airplane that is reliable, meaning things on it do not break often, and easy to maintain, meaning that when things do break, they are easy to fix and/or replace.

E. Judge-ability

All aerobatic maneuvers are performed in an aerobatic box shown in Fig. 3. Larger aircraft are easier to judge because they are more easily seen by the judges on the ground. In the book, Better Aerobatics,[8] the author discusses an optimum location to fly within the box for best scores. If optimization were to push smaller, lighter weight and lower horsepower aircraft, pilots could compensate for the smaller size, by flying in the front half of the box. It has been mentioned by SMEs that aircraft with straight edges on the wings and fewer curves are easier to judge. However, aerodynamic performance pushes for curved edges. This trade-off will have to be analyzed.

F. Manufacturing

Conventionally, aerobatic aircraft have been metal and wood construction. Recently, there has been a trend of using composites due to their high strength to weight ratio. However, on a macroscopic level, composite damage is very difficult to detect.[28] Fatigue occurs in very small areas scattered throughout the structure, and only becomes noticeable once the material is close to failure. These areas are signs of matrix cracking, which will continue to spread under cyclic loads if left unrepaired. While there are a multitude of failure patterns for composites, the most common mode is delamination, or the growth of cracks between plies in a laminate. Delamination is caused by the application of shear loads between plies, which leads to matrix cracking and eventually structural failure. Manufacturing defects are also important to consider, as composite manufacturing processes are complex and relatively new to aviation. Composite failures are a recurring threat in general aviation, with two accidents taking place in August 2015 alone. South African airshow pilot Nigel Hopkins was preparing for a global competition in France when the engine and propeller detached and hit the right wing of his carbon fiber MX2 aircraft. Later that same month, Andrew Wrights carbon fiber Giles G-202 suffered a structural failure just forward of the tail feather junction[29]). These factors should be taken into account and FAR regulations pertaining to composites should be considered in the optimization.

IV. Survey of Existing Aircraft

Another method of generating requirements or revising target metric values will be to examine state-of-the art capabilities and design features through an analysis of existing aerobatic aircraft, paying attention to the historical progression of various quantities. Appendix A gives a list of metrics for aerobatic aircraft flown today.

A. Constraint Analysis

Constraint analysis is a popular method used in the conceptual design of aircraft. Mattingly[30] provides a "master equation" through which point performance metrics of the aircraft can be evaluated to obtain the wing area and thrust of a given concept. With its specific dimensions left undetermined, the initial concept encapsulates three major attributes related to aerodynamics, propulsion, and empty weight that are the basic inputs of the process. Since most aerobatic aircraft use propeller driven piston engines, power-to-weight ratio would be more appropriate to use than thrust-to-weight ratio. Taewoo Nam[31] derived equivalent master equations when power loading is used instead of thrust loading. These equations are appropriate to be used for electric aircraft as well, should aerobatic aircraft take that route. The master equation neglecting wave drag and drag due to non-clean configuration is given by

$$\frac{P_{ref}}{W_{TO}} = \frac{\beta}{\pi_\eta^+ \alpha} \left\{ \frac{q}{\beta \frac{W_{TO}}{S}} \left[K_1 \left(\frac{n\beta}{q} \frac{W_{TO}}{S} \right)^2 + C_{D_0} \right] + \frac{1}{V} \frac{d}{dt} \left(h + \frac{V^2}{2g_0} \right) \right\} V \tag{4}$$

The stall velocity constraint equation is given by

$$\frac{W_{TO}}{S} = \frac{1}{2} \frac{\rho C_{L_{max}} V_S^2}{\beta} \tag{5}$$

Fig. 11 shows a constraint plot of power loading against wing loading for various point performance metrics given in Table 2. Since aerobatic aircraft typically fly close to the ground, they are assumed to fly close to standard sea level and temperature (density, $\rho = 0.002378$ slugs/ft^3 and thrust lapse rate, $\alpha = 1$). The aircraft is assumed to fly with a fuel fraction of 0.99. The stall velocity is taken as 70 mph as specified by regulations. The assumptions made to generate the constraint curves are listed in Table 1 and Table 2. The rate of climb is 5000 fpm, and the acceleration is found by assuming the aircraft should accelerate from 60mph to 120mph in a quarter of the length of aerobatic box (3281 ft/4). The induced drag coefficient is calculated as

$$K_1 = \frac{1}{\pi e AR} \tag{6}$$

Table 1: Aerodynamic characteristics assumed for aerobatic aircraft

Ostwald Efficiency Factor	Aspect Ratio	Zero Lift Drag Coefficient C_{D_0}	Propellor Efficiency	Maximum Lift Coefficient
0.8	5.5	0.03	0.8	1.6

Table 2: Constraint analysis point performance metrics and assumptions

Mission Segment	Velocity (ft/sec)	RoC (ft/sec)	Acceleration (ft/sec^2)	Load Factor
Climb	146	83.33	0	1
Cruise	176	0	0	1
Horizontal Acceleration	176	0	7.0793	1
Sustained Turn	176	0	0	2

Further, data from existing aerobatic aircraft given in Appendix A is also plotted on the constraint diagram. Three groups of aircraft are considered: 4-cylinder, 6-cylinder and 9-cylinder aircraft. Based on the specific model of engine, the aircraft is capable of having a range of available power. To show this variability in power loading, for each category of aircraft, the engine horse power is varied. The values used are given in Table 3 and is plotted as error bars on the constraint diagram. The standard value is shown by a marker and the tails of the error bar shows the variation possible in power loading, with wing loading remaining fixed.

In this analysis, the Cessna 172 and Piper Cherokee perform the 2G turn which corresponds to a bank angle of 60 degrees without much margin. The Sbach 300 and Sukhoi Su-26 are the only aircraft capable of performing the 5000 fpm climb. With the exception of the Beechcraft Bonanza, Cessna and Piper aircraft, all the aircraft studies can perform the required horizontal acceleration. Since the same C_{Lmax} was used to generate all the curves, the stall constraint works out to be a single vertical line. However, some aircraft use flaps to increase the $C_{L_{max}}$ for landing, while others may have a different $C_{L_{max}}$ than the one assumed. Hence, while the aircraft can meet the CFR stall requirements, it appears that it does not on the constraint diagram.

Table 3: Horse power variation for groups of aerobatic aircraft

Number of cylinders	Horse power lower limit	Horse power upper limit
4	150	230
6	260	330
9	350	400

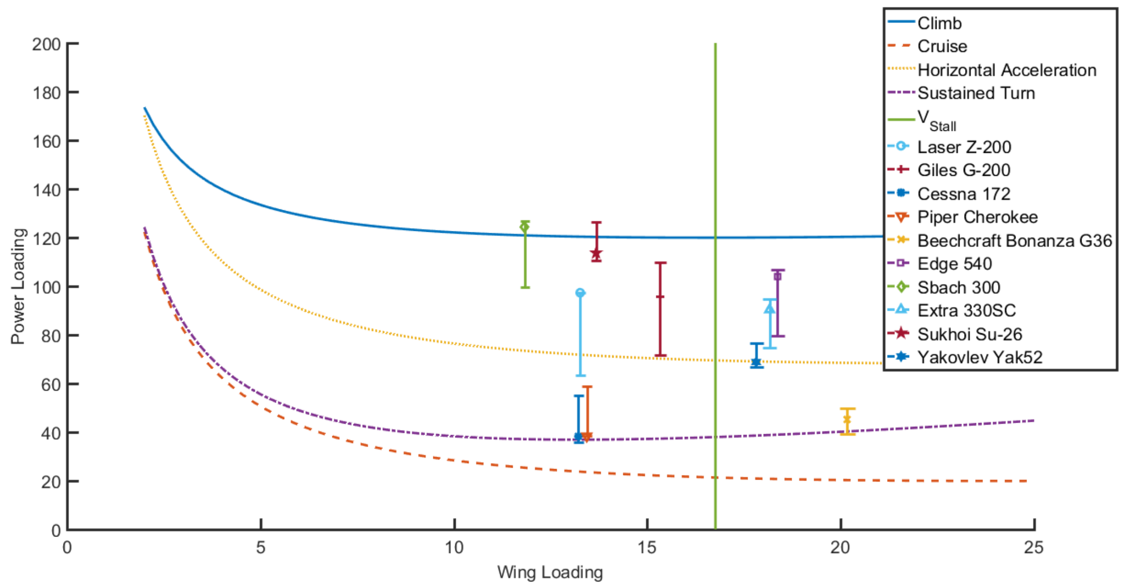

Figure 11: Constraint plot

B. Advantageous Design Features of Existing Aerobatic Aircraft

Some aircraft possess unique design features which enhance performance in certain maneuvers. The optimization algorithm developed should pay special attention to these design features and check if they indeed enhance performance, and also if they can be used synergistically with other design features. Some of these design features are presented in this section.

The MX-2 has improved performance in snap-roll maneuver by moving the vertical stabilizer back several inches so that the horizontal stabilizer is slightly ahead of the vertical.[9] The rationale behind this is: when the rudder and elevator are moved into position for a snap, as the airplane yawed the airflow around the leading edge of the vertical stabilizer disrupted the flow over the stabilizer/elevator, greatly reducing its efficiency. Moving it back mitigates this problem. Similarly, the CAP 232 has a very distinguishable horizontal tail which is ahead of the vertical one.

The Extra 300SC has an enhanced roll rate by using a trapezoidal planform for the ailerons, with the tip aileron chord longer than the root one.[32] It also has a predictable and controllable stall by using a thin airfoils with low radius at the nose. This causes an abrupt fall in the lift curve slope post-stall.

The SBach has good low speed control due to the ailerons being hinged back at 27 percent.[10] Further, contouring the aileron nose and actuation geometry makes the entire surface much more effective at low speeds.

Both the Gamebird GB-1 and the CAP 222 have a ballast system employed to allow for a controllable CG. Such systems are common in gliders with nose weights required to be installed in a 2-seat glider when it flown solo.

During rolls, part of the wing become ineffective. In these situations, the fuselage needs to provide lift to maintain 1g flight condition. A special case, is when the aircraft is rolled to 90 degrees, and the nose of the aircraft is pointed to the sky. The pilot attempts to move the aircraft in a straight line in such a configuration. This maneuver is called knife-edge flight. During such maneuvers, the wings produce negligible lift to support the aircraft. The lift is provided by the thrust and the lift produced by the fuselage. A SME mentioned that the Pitts aircraft with the conventional bungee undercarriage structure are good for 'fuselage lift/flat turning'. These large triangular surfaces are lifting surfaces that bring forward the fuselage lift and therefore result in the CG being further aft when considered in respect to the "mean chord" of the aircraft's side force generation capability. The XA42 has, because of its steel tube gear legs, some narrow but mildly streamlined fairings and give a moderate amount of side force which aides knife-edge flight. Future work will systematically analyze these features to ascertain their effect on performance.

V. Optimization Problem and Possible Analysis Approach

A. Design Variables

When designing an aerobatic aircraft – like any aircraft - there are a number of options that must be selected. Should the aircraft be a high-wing, mid-wing, or low-wing? What is the wing area and aspect ratio? Will this be a composite spar or wooden spar? And many other similar questions must be answered. Some answers will depend on the expected gross weight while some answers impact the gross weight. Almost all answers will in some way impact the metrics previously discussed. One way of showing the options available to the designer is to collect them in what is known as a morphological matrix as shown in Fig. 12. This example morphological matrix was built to show the number of options and decisions that a designer must make as well as to show the utility of organizing the options in a manner such as this. The authors are sure that they have neglected to include an option or option category that is important. Future work will see this matrix continually revised. The advantageous design features of existing aircraft should also be included in the matrix. The matrix shown contains about $2.8 * 10^{25}$ possible alternatives. To analyze that many alternatives would take an almost infinite number of lifetimes. So the list must be refined initially using engineering judgement and input from SMEs. In addition, any incompatibilities between options or between required capability and options should be accounted for as this will reduce the number of possible options as well.[33]

In addition to options, the designer may also be free to vary a design variable like taper ratio, leading edge sweep, percentage span of ailerons, and many others in a continuous fashion. In the morphological matrix, perhaps only leading edge sweep versus no leading edge sweep would be decided. Then the designer must decide on how much to sweep the leading edge. This only increases the number of choices available. It will only be through careful analysis of the options that the optimum configuration (both morphological matrix options and design variable settings) can be selected.

B. Optimization

Optimization problems always have an element of minimizing or maximizing an objective, and typically, the objective's completion will depend on satisfying multiple criterion. These are called multi-objective optimization problems. For example, we may want to maximize the thrust to weight ratio of an aerobatic aircraft, but we also want to minimize drag and cost.

One possible objective function is given in the book "Better Aerobatics" by Alan Cassidy.[8] The author describes a metric named the Aerobatic Performance Index (API) to describe goodness of an aircraft. It combines three quantifiable metrics: power/weight ratio, maximum level speed and maximum roll rate. Cassidy takes an arbitrary value for each parameter and sets that to unity. For example, a maximum level speed of 165 knots would be 1. If an aircraft has a maximum level speed of 120 knots, its index would be 120/165 = 0.73. Similarly, 0.36 hp/kg and 270 deg/sec are set as unity for power/weight ratio and maximum roll rate respectively. Using the equations in the book and recasting using notation in this paper, the power-to-weight index (PWI), max speed index (MSI), roll rate index (RRI) and API are given by

$$PWI = \frac{\frac{P_{ref}\pi_{\eta}^{+}}{W_{TO}}}{0.36} \tag{7}$$

Control System	Autopilot	No Autopilot	Single Axis	Three Axis	
	Control Connections	Control Lines	Electric Servos	Push Rods	
	Control Input Stations	1 Station	2 Stations		
	Control Surface Weighting	Anti Servo Tabs	No Weighting	Servo Tabs	
	Tailplane Trimming	Elevator Spring Trim	No Trimming	Tailplane Trim	
Fuselage	Dual Seating Configuration	Front to Rear	Side by Side	Single Seat	
	Fuselage Construction	Composite	Monocoque	Semi Monocoque	Tubular Steel with Covering
	Fuselage Shape	Airfoil	Bubble With Tail Boom	Teardrop	
	Fuselage Side Force Generators	Large Asymmetric	Large Symmetric	No Side Force Generators	Small Symmetric
	Number of Pilots	1 Pilot	2 Pilots		
	Pilot Location	Aft	Central	Forward	
Landing Gear	Landing Gear Attachment	Fuselage Attachment	Interface Attachment	Wing Attachment	
	Landing Gear Construction	Semi Rigid Tube	Spring Bar	Spring Supported Rigid	
	Landing Gear Type	Bicycle	Tail Dragger	Tricycle	
	Support Fairings	Full Fairing	No Support Fairings	Partial Fairing	
	Wheel Fairings	Complete Wheel Fairing	No Wheel Fairing	Partial Wheel Fairing	
Propulsion	Engine Fuel	Battery	Fuel Cell	Hydrocarbon Liquid	Hydrogen
	Engine Location	Central Mount	Pusher	Tractor	
	Engine Type	Electric	Reciprocating		
	Propeller Duct	Annular Duct	No Duct		
	Propeller Material	Composite Propeller	Metal Propeller	Wood Propeller	
	Propeller Type	Constant Speed	Feathering	Fixed Pitch	Ground Adjustable
Safety System	Fire Protection	Fire Extinguisher	Fire Extinguishing System		
	Pilot Restraint System	Seat with Additional Restraint	Standard Seat		
	Recovery System	Ballistic Recovery System	Ejection Seat	GLOC Prevention	Pilot Parachute
Tail Construction	Horizontal Tail Location	Rear	Three Surface		
	Horizontal Tail Shape	Rounded	Straight Taper Tail	Trapezoid Straight LE	Trapezoid Straight TE
	Horizontal Tail VG	H Tail VGs	No H Tail VGs		
	Tail Configuration	Canard	Conventional	Cruciform	H Tail
	Tail Control Surfaces	Elevator and Rudder	Ruddervator		
	Vertical Tail Location	Above Fuselage	Below Fuselage	Split	
	Vertical Tail Shape	Rectangle V Tail	Rounded V Tail	Straight Taper V Tail	Trapezoid Straight LE V Tail
	Vertical Tail VG	No V Tail VGs	V Tail VGs		
Wing Configuration	Number of Wings	Annular Monoplane	Annular Wing	Biplane	Monoplane
	Side Force Generators	Generators Between Wings	Generators at Center	Generators at Tip	No Generators
	Vertical Wing Location	Biplane Wing	High Wing	Low Wing	Mid Wing
	Wing Airfoil	Semisymmetric Airfoil	Symmetric Airfoil		
	Wing Airfoil Type	LS1 XXXX	NACA 4 Series	NACA 5 Series	NLF1 XXXX
	Wing Control Surfaces	Ailerons	Flaperons	Flaps	Frise Type Ailerons
	Wing Dihedral	Anhedral	Dihedral	Gull	No Dihedral
	Wing Flap Type	Junkers Flap	Plain Flap	Slotted Flap	Split Flap
	Wing Shape	Elliptical	Straight Taper	Tapered Leading Edge	Tapered Trailing Edge
	Wing Stall Strips	Full Span Strips	Inboard Strips	No Strips	Outboard Strips
	Wing Tip Characteristics	Hoerner Tip	Plain	Tip Rake	
	Wing Tip Devices	Box Strut	Plain Tip	Wingtip Fence	Winglet
	Wing Twist	No Twist	Washout		
Wing Structure	Number of Spars	1	2	3	
	Rib Material	Aluminum Rib	Composite Rib	Wood Rib	
	Skin Material	Fabric	Fiberglass Composite	Graphite Composite	Sheet Metal
	Wing Spar Cross Section	Box Spar	I Beam	Rectangle	Tube
	Wing Spar Material	Aluminum Spar	Composite Spar	Steel Spar	Wood Spar
	Wing Support	Full Cantilever	Semi Cantilever	Strut Braced Biplane	Strut Braced Wing

Figure 12: Aerobatic aircraft morphological matrix

$$MSI = \frac{V_{max}}{165} \tag{8}$$

$$RRI = \frac{1.6}{e^{\frac{220}{\phi^{1.1}}}} \tag{9}$$

$$API = (PWI)(MSI)(RRI)50 \tag{10}$$

where P_{ref} is given in horse power and W_TO is given in kilograms, V_{max} in knots and $\dot{\phi}$ in degrees per second. The formulation of the RRI is such that the benefit to the API flattens off above 420 degrees per second.

While API index accounts for three metrics, it fails to account for many others like wing loading, rate of climb, acceleration. Also, specific excess power at maximum throttle is a better indicator than maximum level speed. Further works will attempt to define a well-posed optimization problem.

C. Analysis approches

1. *Vehicle mass and moments of inertia*

The vehicle mass and moments of inertia can be assumed using empirical relations developed using existing aircraft values and taking into account the options selected, for example the method of manufacture. A modern computer aided design tool such as Dassault System CATIA, SolidWorks or AutoDesk Inventor can be used to create a virtual prototype of the design. With correct densities of materials included, a very good estimate of mass and moment of inertia can be queried from the model. However, a detailed virtual model such as this requires a significant investment in time and is typically only used once most of the decisions have been made. Thus the empirical relations or a simplified component build-up would most likely be used during optimization.

2. *Aerodynamics*

Many of the metrics will depend in some way on the aerodynamics of the vehicle. Basic parameters like vehicle lift, drag, and pitching moment versus angle of attack and sideslip will have to be calculated for the full-envelope. These parameters may be calculated with varying degress of fidelity, from medium fidelity methods like strip theory[2] and vortex lattice methods[34,35] to high fidelity methods like CFD.

The Extended Design Structure Matrix (XDSM) is a standardized architecture (developed by[36]) that helps solving multidisciplinary design problems within an optimization framework. Each analysis is on the diagonal. Inputs to each analysis is found by looking at the corresponding column, while outputs from each analysis is found on the corresponding row. The thick gray line represents data flow, whereas the thin black line represents process flow. The aerobatic wing optimization methodology is represented using the XDSM in Fig. 13.

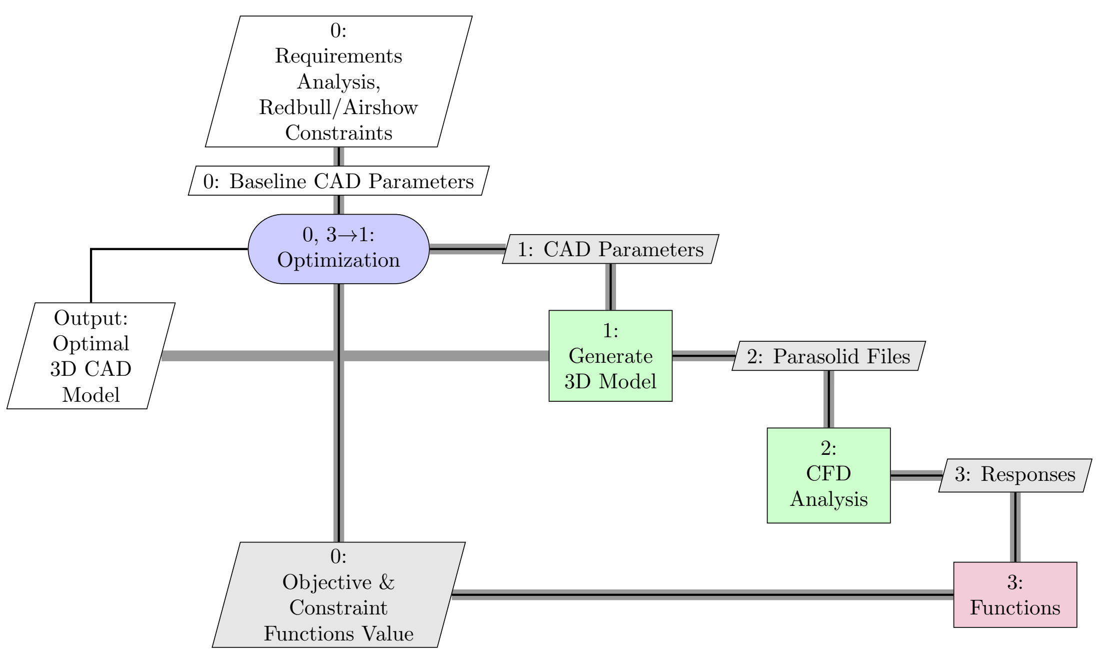

Figure 13: Extended Design Structure Matrix (XDSM) for aerobatic aerodynamic optimization[36]

An example implementation of the process shown in Fig. 13 is as follows: the regulations of the Red Bull Air Race or World Aerobatic Series Competition are provided as constraints to the optimizer. The metrics-of-goodness obtained from the requirements analysis are also used as inputs to the optimizer. The geometric parameters are populated in an Excel file. This file is used to generate a 3D model in AutoDesk Inventor. Parasolid files are obtained from Inventor which is fed into Star-CCM+. CFD analysis is performed in Star-CCM+. Responses of interest are extracted. The optimizer, HEEDS evaluates the objective function and constraint function and makes appropriately updates the Excel file. This process is iterated till an optimum design which meets all the constraints is reached. To begin the optimization process, a baseline design, such as the Extra 300 wing can be provided.

The drawback however to using CFD would be the computational expense, especially when studying the aerodynamics in figures such as aileron rolls, snap rolls, spins, and loops.

3. Performance

Basic performance numbers like max level flight speed, range, and specific excess power, etc. can be calculated with estimates of gross weight and basic aerodynamic parameters. Max roll rate will require aerodynamics of control surface deflection and roll inertia combined in a flight dynamics model. Other edges of the flight envelope such as max positive and negative g limits and maximum dive speed will require a combined aerodynamic and structural analysis. This type of analysis is also needed to understand the relationship between aileron force and the torque put on the wing's half span that could lead - with a non-rigid wing structure - to control reversal. This is caused by the aileron that reduces or reverses camber (aileron up) causing a twisting moment on the wing which actually increases the angle of attack.

4. Flight mechanics

Due to the importance of handling qualities to the aerobatic pilot, a way to evaluate the flight mechanics is required. Linear control theory can be used to understand the basic stability and control derivatives from various trimmed flight conditions. This will give a number that may point to goodness provided that information from pilots is received regarding the handling of a variety of existing aerobatic aircraft and also that the same linear flight mechanics analysis is performed for these aircraft so that a correlation, if any, can be found between the values of the derivatives and the comments from the expert pilots. To run the models through an analysis of some of the more interesting figures mentioned will require a non-linear flight mechanics analysis with the aerodynamics in almost all attitudes considered. The fidelity of the aerodynamic analysis in some attitudes - namely those outside the flight envelope – may be grossly approximated as the time the aircraft will spend in these attitudes will be negligible compared to the time within the flight envelope. A MATLAB Simulink model similar to that used in[37] could be used, provided the aerodynamic models and estimates for the mass, CG location, and moments of inertia adequately represent the chosen configuration and design variable settings.

5. Structures and Aeroelasticity

As with aerodynamics, varying levels of fidelity can be used to analyze structures. The simplest would be to assume the wing is a cantilever beam subjected to only aerodynamic loads. However, when aerobatic aircraft perform high-g maneuvers, inertial loads also play a significant role.

The structure can be analyzed using a stick and panel method for each rib and Timoshenko beam analysis for the spars. The approach is as described by Hodges.[38] The approach has two steps: 1) The cross-sections are analyzed individually to obtain effective stiffness matrices along the spanwise direction, and 2) solve a 1D curve to obtain the normal and shear stresses in the body. A number of failure modes such as buckling, max stress, max displacements; will be tested to ensure the structure will not fail during the maneuver. Also, aeroelastic effects[39] become important and need to be analyzed.

VI. Conclusion

In this paper, we first presented a brief history of aerobatic aircraft to understand the current state-of-the-art. Next, using regulations, performance metrics, SME inputs and analysis of existing aircraft, metrics to define "goodness" of an aerobatic aircraft were presented. Desirable design features were also highlighted.

A morphological matrix which can used to decide an aerobatic aircraft configuration was given. Finally, possible analysis approaches to evaluate the metrics was discussed.

Ongoing development of a framework which allows for aero-structural optimization is briefly talked about. It will be improved to include flight dynamics. Future work will define a more all-encompassing objective function and attempt to optimize aerobatic aircraft.

Acknowledgments

The authors would like to acknowledge all the SMEs who contributed to this work. Particularly, Alan Cassidy who provided insights on many features and metrics to be used. Jerry Riedinger provided input about the required climb rate, need to accelerate quickly and spin recovery. Spencer Suderman provided inputs on design features which improve knife-edge flight . Peter Pengilly suggested using specific excess power as a metric. Other SMEs whose help was invaluable are Robert Armstrong, Marty Flournoy, Mark Fullerton, Benjamin Freelove, Steve Grohsmeyer, and Devin York.

We also acknowledge undergraduate students at the School of Aerospace Engineering, Georgia Tech: Yash Chandramouli for the work on control systems, Joshua Perry for his work on composites used in aerobatic aircraft, Matt Schmit and Joshua Price for creating the morphological matrix, and Woradorn Kamolpornwijit who created a parametric CAD model of an aerobatic wing.

Appendix B: Existing Aerobatic Aircraft Specifications

Table 4 enumerates the specifications of popular existing aerobatic aircraft. The aircraft are divided into three categories based on the number of engine cylinders.

Table 4: Existing Aerobatic Aircraft Specifications

Aircraft	P_{ref}	S (ft^2)	b (ft)	W_E (lbs)	W_{TO} (lbs)	$\frac{dh}{dt}$ (ft/min)	V_S (mph)	V_{NE}	$\dot{\phi}$ (deg/sec)
4 cyllinder									
Laser Z-200	230	98	24.33	950	1300	2500	64	210	
Giles G-200	200	75	20	750	1150	4100	66	253	420
Cessna 172N	160	174	36.08	1379	2300	770	50.6	181.82	
Piper Cherokee	150	160	30	1290	2150	660	55.23		
6 cylinder									
Beechcraft G-36	300	181	33.5	2625	3650	1230	68	236	
Edge 540	340	98	24.17	1170	1800	3700			480
Sbach 300	324	121.1	24.61	1257	1433	4070		276	380
Extra 330SC	330	105.6	24.6	1291	1918	3200	70	253	400
9 cylinder									
Sukhoi SU-26	360	127.34	25.59		1741.7	3540		279	315
Yakovlev Yak-52	360	161.5	30.52	2238	2877	1378	69	279	

References

[1]Dantsker, O. D., Johnson, M. J., Selig, M. S., and Bretl, T. W., "Development of the uiuc aero testbed: a large-scale unmanned electric aerobatic aircraft for aerodynamics research," *AIAA) Applied Aerodynamics Conference*, Vol. 2, 2013.

[2]Selig, M. S., "Real-Time Flight Simulation of Highly Maneuverable Unmanned Aerial Vehicles," *Journal of Aircraft*, Vol. 51, No. 6, 2014, pp. 1705–1725.

[3]Michael, O., Zeune, C., White, T., and Kudla, T., "Wind Tunnel Evaluation of Powered Static Aerodynamics of an Aerobatic UAV," 2013.

[4]Guo, S., "Aeroelastic optimization of an aerobatic aircraft wing structure," *Aerospace Science and Technology*, Vol. 11, No. 5, 2007, pp. 396–404.

[5]H, P. C., "Biplane construction," Oct. 3 1972, US Patent 3,695,557.

[6]Wagstaff, P., "Monoplane Revolution A game changer in the world of aerobatic competition," April 2013, [Online; Published 23-April-2013].

[7]Inc, Z. A., *The Zivko Edge*, http://www.zivko.com/edge/downloads/PParticle01.pdf, 2001.

[8]Cassidy, A., *Better Aerobatics*, Freestyle Aviation Books, United Kingdom, 2003.

[9] Davisson, B., “Gary Ward and the MX2 Between the Sun and the Fun the story is told,” *Sport Aerobatics*, June 2007.

[10] Davisson, B., “The Sbach 300 Yet another acro era dawns,” *Sport Aerobatics*, June 2008.

[11] Davisson, B., “Sbach 342 The newest, nimble g-machine,” *Sport Aerobatics*, April 2009.

[12] Bergqvist, P., “We Fly GB1 Gamebird,” *Flying Magazine*, October 2016.

[13] Michailovich, J. K., “Aerobatic Airplane,” 03 1993.

[14] Rancourt, D., Lavoie, M., and Charron, F., “ProjetEpervier: Design, Build and Test Flight of a Full-Scale Aerobatic Aircraft at the Université de Sherbrooke,” 2014.

[15] Iscold, P., Utsch, R., and Lima, K. d., “Lei de controle para loop acrobático Otimo,” *Society of Automotive Engineers*, 2004.

[16] Paulo, H., Cimini Jr, C. A., and Ribeiro, R. P., “A brazilian experience in teaching aircraft design,” .

[17] Stewart, E., “The Next World Speed Record,” *Air and Space Magazine*, August 2015.

[18] *23.333 Flight envelope.*, Code of Federal Regulations.

[19] Opperman, G., “BRS: The Benefits of Whole Airplane Parachute Systems,” 2015.

[20] Severin, G. I., “Emergency escape method for an aircraft crew,” March 28 2000, US Patent 6,042,054.

[21] Wagstaff, P. and Cooper, A. L., *Fire and air: a life on the edge*, Chicago Review Press, Inc., Chicago, Illinois, 1997.

[22] Cooper, G. E. and Harper Jr, R. P., “The use of pilot rating in the evaluation of aircraft handling qualities,” Tech. rep., DTIC Document, 1969.

[23] Gertsen, W. and SHOMBER, H., “Longitudinal handling qualities criteria-An evaluation.” *Journal of Aircraft*, Vol. 4, No. 4, 1967, pp. 371–376.

[24] Gibson, J. C., *The definition, understanding and design of aircraft handling qualities*, Delft University of Technology, 1995.

[25] *Pilot’s handbook of aeronautical knowledge*, Federal Aviation Administration, United States Department of Transportation, Oklahoma City, OK 73125, United States, 2016.

[26] Patricia Trenner, A. and Magazine, S., “How Things Work: Flying Upside Down,” 2002.

[27] Moir, I. and Seabridge, A., *Aircraft systems: mechanical, electrical and avionics subsystems integration*, Vol. 52, John Wiley & Sons, 2011.

[28] Bureau, A. T. S., *Fibre composite aircraft capability and safety*, Australian Transport Safety Bureau, PO Box 967, Civic Square ACT 2608, 2007.

[29] Board, N. T. S., “NTSB Identification: ERA15FA331,” 2015.

[30] Mattingly, J. D., *Aircraft engine design*, Aiaa, 2002.

[31] Nam, T., *A generalized sizing method for revolutionary concepts under probabilistic design constraints*, Ph.D. thesis, Citeseer, 2007.

[32] Davisson, B., “The Extra 300SC Walter Extras New Unlimited Contender,” *Sport Aerobatics*, October 2008.

[33] Schmit, M., Briceno, S., Collins, K., Mavris, D., Lynch, K., and Ball, G., “Semantic design space refinement for model-based systems engineering,” *Systems Conference (SysCon), 2016 Annual IEEE*, IEEE, 2016, pp. 1–8.

[34] Murua, J., Palacios, R., and Graham, J. M. R., “Applications of the unsteady vortex-lattice method in aircraft aeroelasticity and flight dynamics,” *Progress in Aerospace Sciences*, Vol. 55, 2012, pp. 46–72.

[35] Melin, T., “A vortex lattice MATLAB implementation for linear aerodynamic wing applications,” *Master’s Thesis, Department of Aeronautics, Royal Institute of Technology (KTH), Stockholm, Sweden*, 2000.

[36] B.Lambe, A. and Martins, J. R., “Extensions to the Design Structure Matrix for the Description of Multidisciplinary Design, Analysis, and Optimization Processes,” *Structural and Multidisciplinary Optimization*, 2012, pp. 273–284.

[37] Chakraborty, I., Lozano, B., and Mavris, D. N., “Pilot-Friendliness Considerations for Personal Air Vehicle Flight Control Systems,” *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015, p. 2852.

[38] Hodges, D. H., “Nonlinear composite beam theory,” *Progress in astronautics and aeronautics*, Vol. 213, 2006, pp. 304.

[39] Patil, M. J., Hodges, D. H., and S. Cesnik, C. E., “Nonlinear aeroelasticity and flight dynamics of high-altitude long-endurance aircraft,” *Journal of Aircraft*, Vol. 38, No. 1, 2001, pp. 88–94.